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ANALYSIS OF THE SLOW-WAVE STRUCTURES USED IN THE MILLIMETER RANGE DEVICES

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Keywords: *resonator rectangular and axially-symmetric slow-wave structures, electrodynamic characteristics, program HFSS, millimeter range, TWT modeling, discrete approach.*

In this paper the slow-wave structures and their models, which are used for development of the millimeter range devices, are considered. The travelling-wave tubes (TWTs) of the millimeter range use rectangular and axially-symmetric resonator slow-wave structures. Analysis of these slow-wave structures was performed using HFSS program for 3D-modeling [1]. Dispersion characteristics were calculated by program outlined in the paper [2]. These characteristics are used to build the model of the slow-wave structure's cell. The peculiarities of the interaction between the electrons and the field in the TWT with resonator slow-wave structures are determined by the nature of the field distribution in such structure. The discrete approach is the most common for solving problems of this type [3]. The difference form of the electrodynamic excitation theory applied to the description of the discrete interaction is justifying the use of a mathematical model.

For a description of the TWT with the discrete interaction, in which the phase of the field in the interaction gaps in the longitudinal remains constant, the use of the difference equation is electrodynamically reasonable.

The more precisely defined the coefficients of the finite difference equations, the more accurate the mathematical model of the discrete interaction becomes. These coefficients have a certain electrodynamic meaning and are defined via coefficients of the quadripole transmission matrix derived from the sextopole if there is no the exciting current. The accuracy of the restoration of the electrodynamic characteristics of the modeled resonator slow-wave structures is determined by the coefficients of the quadripole obtained. Therefore, the correct selection of these coefficients provides a correct description of the discrete processes of interaction in travelling-wave tubes as well as the electrodynamic processes in the slow-wave structures.

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1. Introduction

The development of the radar, communication, and control systems in the 8-mm wavelength range puts forward new power and working bandwidth requirements on the amplifiers characteristics for this range.

Due the overflow of the satellite communication channels operating in the centimeter wavelength range, there was a transition of the satellite and other communication systems to a higher frequencies. The 20...30 GHz frequencies are intended for civil communication systems, while the 20...44 GHz frequencies are intended for a military communication systems. This shift to higher frequencies causes the need for the amplifying devices such as travelling-wave tubes (TWTs) with the high level of the output power in this range, more than 1000 W in the frequency range more than 5…10% to be exact.

When creating a modern and advanced military control systems of the precision weapons and the radiovision, the combination of a high power and a wide amplification band of the microwave amplifier is required. In particular, it is important in the development of a missile guidance systems with a radar homing and a goals recognition systems involving the use of the radar maps and the radio images of the observed objects. The need to create powerful broadband microwave amplifiers is also caused by the development needs of the radar weapons systems, for example, the airborne radars. Basic requirements for a new perspective radar weapon systems are following: the broad frequency band, the use of superresolution signals, the combined use of a wide set of the probing signals, the solutions of the electronic warfare problems, the increased range on targets, including barely visible ones. The fulfillment of these requirements with the use of traditional microwave amplifiers is virtually impossible to implement, and therefore the problem of searching for a new ways and methods of their construction rises.

The currently achieved level of output power and the 8-mm range TWT frequency bandwidth are determined by the selection of the optimal parameters of used periodic slow-wave structures (SWSs) of "chain of coupled resonators" – type.

The potential of the millimeter range far from being exhausted, as the most of the radars and modern information and communication systems, including those related to the space communication, are operating in this range, which in itself speaks about the prospects of the microwave technology development. One of the most important tasks in the development of new devices and devices operating in the microwave range is the construction of mathematical and computer models, not only adequate in relation to the laws of physics and giving the results corresponding with a real systems, but also being economical in terms of computational burden.

This paper deals with the widely applied in the amplifying systems medium power all-metal resonator slow-wave structures used due to their substantial heat sink. These slow-wave structures are three-dimensional, so their computer simulation based on strict electrodynamic laws is extremely demanding on computing power, which makes the problem of constructing the exact and at the same time simple models for calculating of resonator slow-wave structures quite urgent.

2. Model of slow-wave structure cell

In the millimeter range traveling-wave tubes the rectangular and axially-symmetric slow-wave structures (SWSs) presented in Figures 1 and 2 are used.

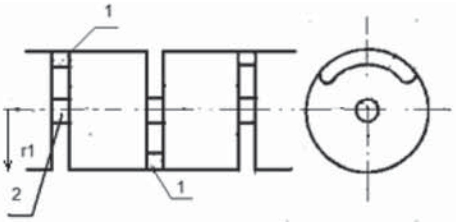

Fig. 1. Axially-symmetric resonator slow-wave structure (SWS): 1 –slot channel, 2 – transit channel, r1 – resonator radius

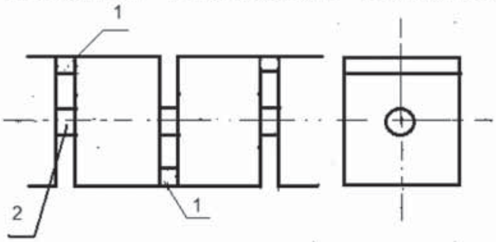

Fig. 2. Rectangular resonator SWS

The main features of these slow-wave structures are the small dimensions and the absence of protrusions on the diaphragms.

All-metal resonator slow-wave structures (SWS) are transmission lines obtained by connecting identical cells into a chain. These cells are coupled by waveguide channels. These channels can be divided into the input channels $S_\alpha{}^1$, $\alpha=1,2,\ldots k$ and output channels $S_\alpha{}^2$, $\alpha=1,2,\ldots l$. Due to the the periodicity of the investigated slow-wave structures, the distance between the sections $S_\alpha{}^1$ and $S_\alpha{}^2$ equals the period of the slow-wave structure D, and the number of input channels is equal to the number of output channels ($k=l=N$).

The components of the electromagnetic fields at the boundaries of sections $S_\alpha{}^{1,2}$ are connected by the expression:

$$\begin{pmatrix} \vec{a}_1 \\ --- \\ \vec{b}_1 \end{pmatrix} = A^N \begin{pmatrix} \vec{a}_2 \\ --- \\ \vec{b}_2 \end{pmatrix}, \qquad (1)$$

where $\vec{a}_{1(2)}$, $\vec{b}_{1(2)}$ are vectors, which represent a set of complex amplitudes in the sections $S_\alpha{}^{1,2}$, A^N is matrix linear operator of the form:

$$A^N = \begin{pmatrix} A_{11} & A_{12} \cdots & A_{12N} \\ A_{21} & A_{22} \cdots & A_{22N} \\ . & . \;\cdots & . \\ A_{2N1} & A_{2N2} \cdots & A_{2n2n} \end{pmatrix} \qquad (2)$$

Using the operator A^N from (1), it is possible to obtain all possible operating modes of the considered SWS. If the elements of the operator A^N are known to us, the SWS is completely formalized, therefore, we can calculate all of its electromagnetic characteristics [2].

The normal wave field in the volume of the considered cell is the completely determined by the tangential components of electromagnetic fields in sections $S_\alpha{}^{1(2)}$, which obey the Floquet conditions [2]:

$$\vec{E}_\alpha^{\tau N}(x,y,z)=\vec{E}_\alpha^{\tau N}(x,y,z+D)e^{ih_nD}, \quad \vec{H}_\alpha^{\tau N}(x,y,z)=\vec{H}_\alpha^{\tau N}(x,y,z+D)e^{ih_nD}, \qquad (3)$$

where h_n is propagation constant of the normal wave within n-th cell having period D. Considering (1), rewrite the expression (3) relative to the vectors of complex amplitudes as:

$$\begin{pmatrix} \vec{a}_2 \\ --- \\ \vec{b}_2 \end{pmatrix} = \begin{pmatrix} \vec{a}_1 \\ --- \\ \vec{b}_1 \end{pmatrix} * e^{-ih_nD} \qquad (4)$$

Taking into account (4), we remove $\vec{a}_2$ and $\vec{b}_2$ from (1) and get:

$$A^N \begin{pmatrix} \vec{a}_1 \\ --- \\ \vec{b}_1 \end{pmatrix} = \begin{pmatrix} \vec{a}_1 \\ --- \\ \vec{b}_1 \end{pmatrix} * e^{-ih_nD} \qquad (5)$$

This equation (5) is an algebraic formulation of the problem of the considered SWS eigenwaves, the cells of this SWS are represented by 2N-pole described by the operator A^N.

For this system, there is a nontrivial solution in the case of the fulfillment of the condition [2]:

$$\det(A^N - \lambda^N E) = 0, \qquad (6)$$

where $\lambda^N = \exp(-ih_nD)$ are eigenvalues of the matrix A^N allowing to obtain the values of propagation constants h_n of 2N-pole, which is a model of the slow-wave structure cell; E – the identity matrix. As shown in [2], the condition (6) is the dispersion equation of the 2N-pole normal waves, from which we can derive an equation of the form $\varphi = f(\omega)$ taking into account dependence of the elements of the matrix operator A^N from frequency ω.

For a description of the SWS cell the A^N operators of different types can be used depending on the number of transmission channels of microwave energy [2]. The simplest option corresponds to the slow-wave structure without transit channel (Figure 3, Figure 4), described by the quadripole (7).

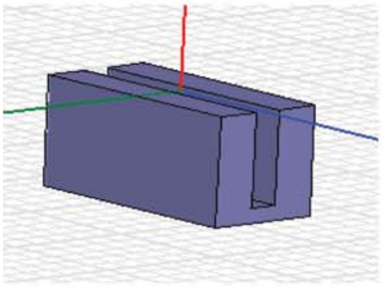

Fig. 3. Cell of SWS with a rectangular cross section (cut by interaction gaps)

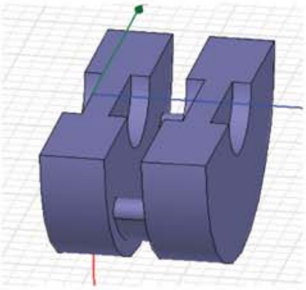

Fig. 4. Cell of axially-symmetric SWS (cut by interaction gaps)

In this case, the slow-wave structure cell is described by the quadripole:

$$\begin{vmatrix} A_{11} - \lambda^{1,2} & A_{12} \\ A_{21} & A_{22} - \lambda^{1,2} \end{vmatrix} = 0 \qquad (7)$$

This slow-wave structure will be characterized by the two (complex conjugate) propagation constants of the forward and the backward waves and their impedances (Figures 5-8).

In case of the slow-wave structures used in the millimeter devices, the rectangular and axially-symmetric resonator slow-wave structures with the transit channel described by octopoles are used. Such slow-wave structures are shown in Figures 9, 10.

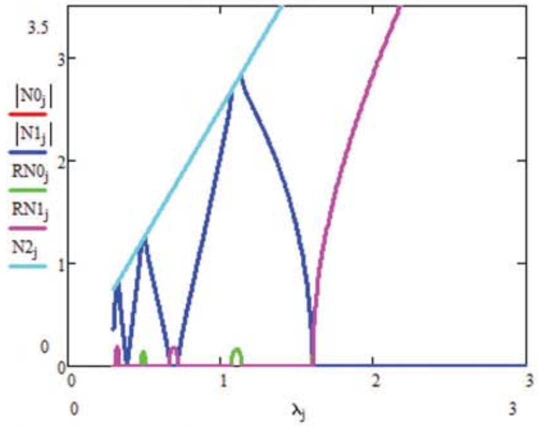

Fig. 5. Slowing factor in the rectangular SWS

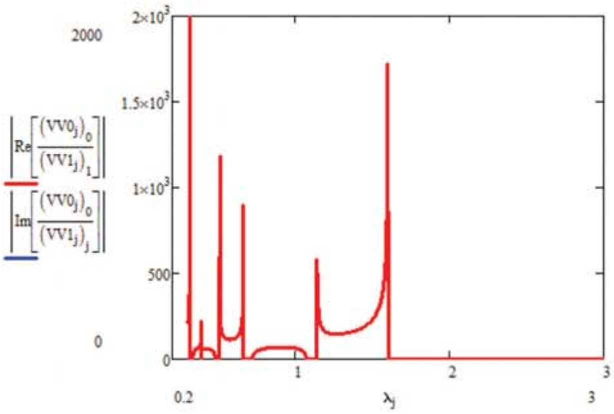

Fig. 6. Impedance of the rectangular SWS

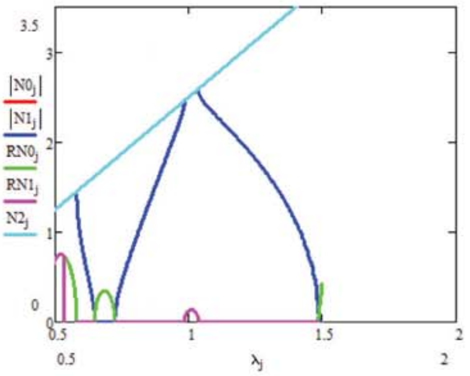

Fig. 7. Slowing factor in the axially-symmetric SWS

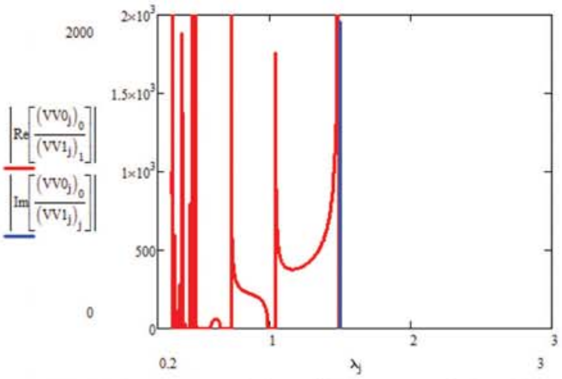

Fig. 8. Impedance of the axially-symmetric SWS

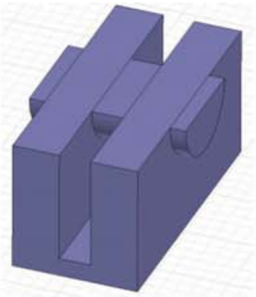

Fig. 9. Rectangular SWS cell with the transit channel

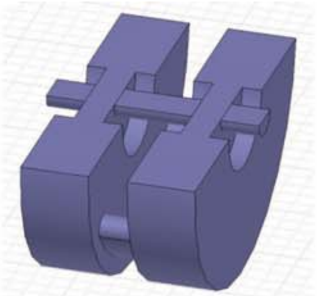

Fig. 10. Axially-symmetric SWS cell with the transit channel

The slow-wave structure cell in this case is modeled by the octopole. The eigenvalues of the octopole define four decisions (modes), the first two of which (the complex conjugate) correspond to the forward and backward waves propagating in the SWS. The second two correspond to the resonant modes. The characteristic impedances are determined by the eigenvectors of the octopole transmission. The results of the dispersion characteristics calculation with two microwave energy transmission channels are shown in Figures 11-16.

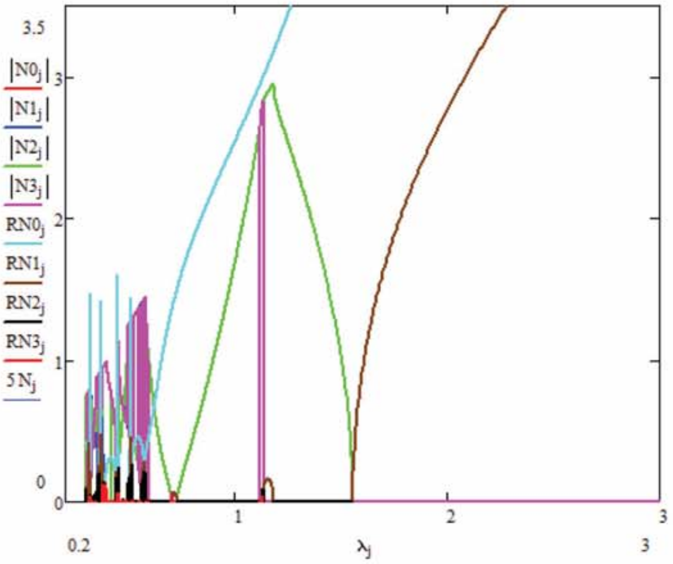

Fig. 11. Dispersion characteristics of the millimeter range rectangular SWS of "chain of coupled resonators"-type

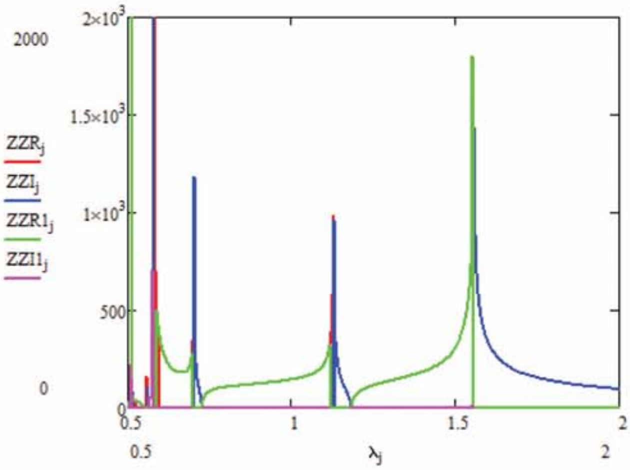

Fig. 12. Slot channel's characteristic impedance of the millimeter range rectangular SWS of "chain of coupled resonators"-type

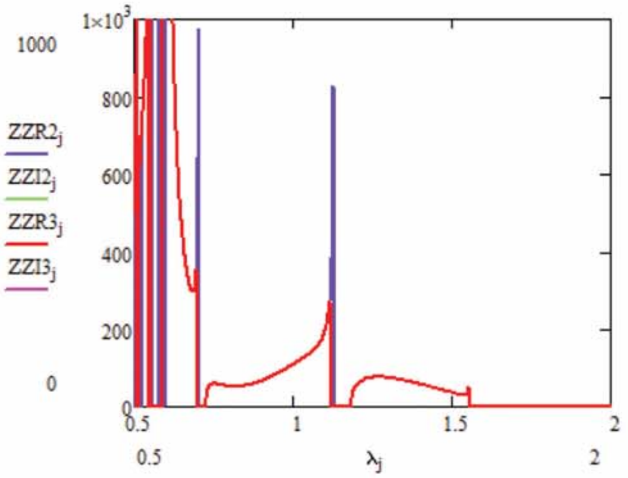

Fig. 13. Transit channel's characteristic impedance of the millimeter range rectangular SWS of "chain of coupled resonators"-type

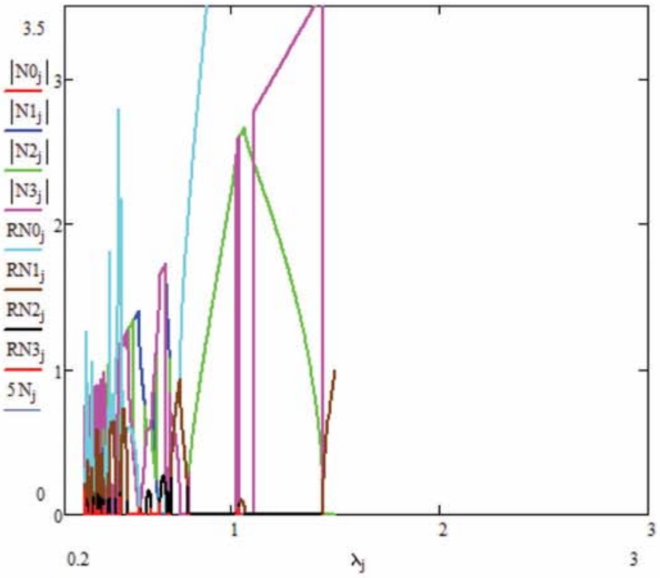

Fig. 14. Dispersion characteristics of the millimeter range axially-symmetric SWS of "chain of coupled resonators"-type

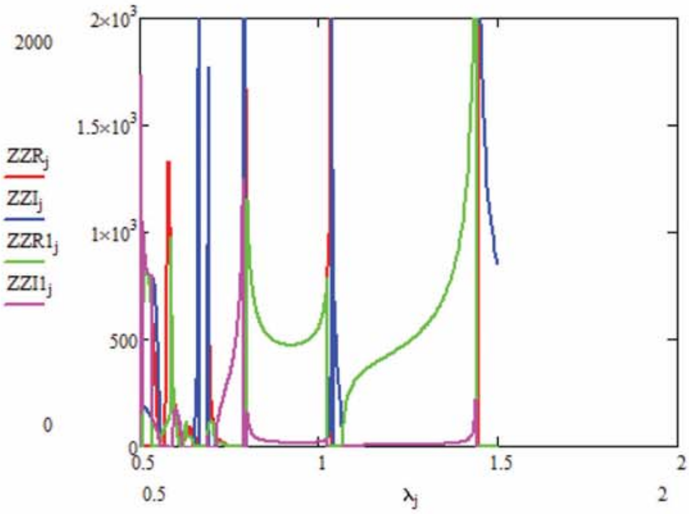

Fig. 15. Slot channel's characteristic impedance of the millimeter range axially-symmetric SWS of "chain of coupled resonators"-type

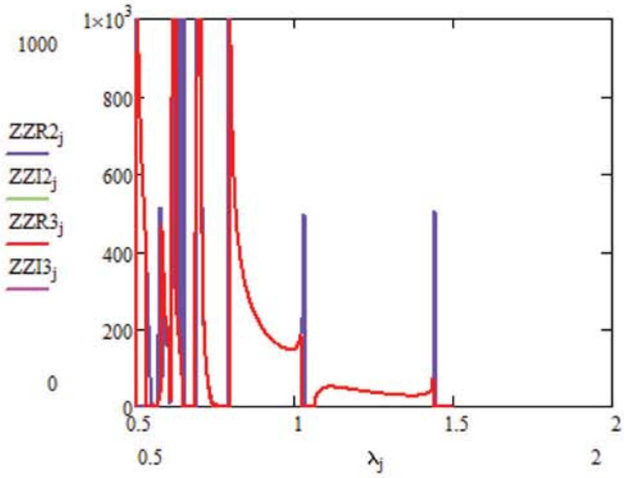

Fig. 16. Transit channel's characteristic impedance of the millimeter range axially-symmetric SWS of "chain of coupled resonators"-type

As seen from the calculation results, the introduction of even small radius transit channel (r=0.05mm) affects the position of the passbands and attenuation bands as well as the characteristic impedance of the SWS's microwave energy transmission channels. Thus, when designing the millimeter range devices the SWS models with transit channel should be used.

3. Modeling of the TWT section excited by current

The interaction of electrons with the electromagnetic wave in traveling-wave tubes is determined by the field distribution in the SWS. Due to the fact that the field amplitudes vary from maximum in the interaction gap to minimum in the transit channel, the electron beam actually interacts with the field in a limited area discretely. The discrete approach to problems of this type is the most common.

Studies carried out in the work [3] showed that using formal transformations the known equations of excitation are reduced to the finite difference equations of two types:

$$V_{n+1}-(A_{11}+A_{22})V_n+V_{n-1}=\left[(A_{13}A_{31}+A_{32}A_{23})-(A_{11}+A_{22})A_{33}\right]J_n+$$
$$+A_{33}(J_{n-1}+J_{n+1})-\left[A_{31}(A_{13}A_{22}-A_{23}A_{12})-A_{32}(A_{13}A_{21}-A_{23}A_{11})\right]J_{n-1} \quad (8)$$

$$V_{k+1}-(A_{11}+A_{22})V_k+V_{k-1}=-A_{12}J_k \quad (9)$$

The coefficients of these equations can be expressed through the transmission matrix coefficients of the sextopole modeling the resonator SWS cell excited by current. To justify the choice of a mathematical model used for describing the process of discrete interaction the difference form of the electrodynamic excitation theory will be used [4].

For a description of the TWT with discrete interaction in which the phase of the field in the interaction gaps in the longitudinal direction remains constant the use of a differential equation (9)is electrodynamically justified. This equation corresponds to sextopole, in which the inputs of the excitation by current and the inputs of the excitation by field are combined. In this case, the TWT section excited by a given current is modeled by the chain of the sextopoles derived from the octopoles when the microwave energy transmission channels are combined (Figure 17), which makes it easy to take into account the boundary conditions at the ends of the section, as well as the reflections arising from the merging in the section of the non-identical cells. The octopoles are obtained by the 3D-modeling of the slow-wave structures cells distinguished by the interaction gaps (Figures 9, 10).

The more precisely defined the coefficients of the finite difference equations, the more accurate the mathematical model of the discrete interaction becomes. These coefficients have a certain electrodynamic sense and are calculated through the transmission matrix coefficients of the quadripole derived from the sextopole provided that there is no exciting current. In turn, this quadripole is the mathematical model of the resonator slow-wave structure cell. The restoration accuracy of the modeled resonator SWS's electrodynamic characteristics is determined by the coefficients of the obtained quadripole. Therefore, the correct selection of these coefficients provides the correct description of the discrete interaction in traveling-wave tubes and electrodynamic processes in the slow-wave structures [5].

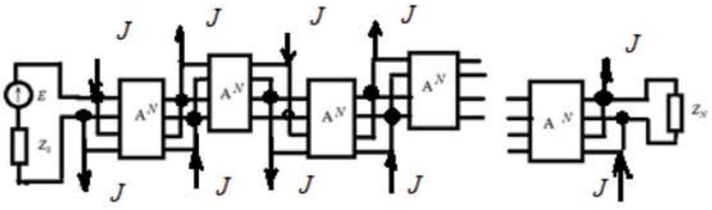

Fig. 17. Model of the TWT section

4. Conclusion

On the Figures 11-16 the dispersion characteristics of the millimeter range slow-wave structure of "chain of coupled resonators"-type with the transit channel (r = 0.05mm) are shown. It is easy to see that even such a small aperture has an impact on the dispersion characteristics, in particular on the characteristic impedance. This effect increases with the transit channel radius. Thus, the correct calculation of the dispersion characteristics will enable a more targeted selection of parameters and characteristics when designing the millimeter range traveling-wave tubes, built on the basis of these slow-wave structures.

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АНАЛИЗ ЗАМЕДЛЯЮЩИХ СИСТЕМ, ИСПОЛЬЗУЕМЫХ В ПРИБОРАХ МИЛЛИМЕТРОВОГО ДИАПАЗОНА

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Аннотация

Рассматриваются замедляющие системы и их модели, которые используются при проектировании приборов миллиметрового диапазона. В лампах бегущей волны миллиметрового диапазона используются прямоугольные и аксиально-симметричные резонаторные замедляющие системы (ЗС). Анализ этих замедляющих систем проводился с использованием 3D моделирования по программе HFSS [1]. Дисперсионные характеристики рассчитывались по программе, изложенной в [2]. Полученные в результате расчета характеристики используются для построения модели ячейки замедляющей системы. Особенности взаимодействия электронов и поля в ЛБВ с резонаторными замедляющими системами определяются характером распределения полей в такой системе. Наиболее общим при решении задач данного типа является дискретный подход [3]. При описании дискретного взаимодействия применение разностной формы электродинамической теории возбуждения [4] позволяет сделать выбор между той или иной математической моделью.
Для описания ЛБВ с дискретным взаимодействием, в которых фаза поля в зазорах взаимодействия в продольном направлении остается постоянной, электродинамически обоснованным является использование разностного уравнения. Чем точнее заданы коэффициенты конечно-разностного уравнения, тем более адекватной становится и математическая модель дискретного взаимодействия. Эти коэффициенты обладают определенным электродинамическим смыслом и задаются через коэффициенты матрицы передачи четырехполюсника, получаемого из шестиполюсника при условии, что возбуждающего тока нет. Данный четырехполюсник, в свою очередь, является математической моделью ячейки резонаторной замедляющей системы. Точность восстановления электродинамических характеристик моделируемой резонаторной ЗС определяется коэффициентами полученного четырёхполюсника. Следовательно, верный подбор данных коэффициентов обеспечивает правильное описание и процессов дискретного взаимодействия в лампах бегущей волны, и электродинамических процессов в ЗС.

Ключевые слова: *резонаторные прямоугольные и аксиально-симметричные замедляющие системы, электродинамические характеристики, программа HFSS, миллиметровый диапазон, моделирование ЛБВ, дискретный подход.*

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